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Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system

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ABSTRACT

Grain-legume plants fix atmospheric nitrogen in the soil and thus do not need nitrogen fertilizers. Therefore, grain-legumes can potentially decrease global warming, as nitrogen fertilization is responsible for half of all agricultural greenhouse gas emissions. Moreover, grain-legumes have many functional and nutritional properties both as feed and food. Despite the fact that the European Union has granted considerable subsidies to promote grain-legume cultivation, their production continues to fall and there has been no satisfactory explanation as to why. This study provides an answer by showing that a situation of technological lock-in has resulted from the co-evolution of crop systems, based on an agrochemical paradigm, public policies, and market dynamics that promote cereals. This process began with the historical choice by European and French public institutions to relegate grain-legumes to feed in direct competition with imported soybeans. Moreover, interrelated factors, such as breeding selection, public subsidies, and food systems, have favored increasing returns to adoption for cereals to the detriment of grain-legumes. Finally, the evolutionary economics approach used here identified several actions that must be implemented together, such as agricultural cost-accounting methods, nitrogen management, institutional innovations, and market outlets to promote grain-legumes and move towards more sustainable agriculture.

1. Introduction

Agriculture accounts for 11% of the world's greenhouse-gas (GHG) emissions and 24% when forestry and other land use measures, including deforestation,[1] are taken into account (IPCC, 2014). Agricultural emissions are specific in that they are mostly non-energy-related and are linked to biological processes. In France, agriculture accounts for almost 20% of GHG emissions (excluding land use). Of that 20%, 10% is due to the nitrous oxide emitted during the de-nitrification process of nitrogenous fertilizers used on arable land, 8% from methane from cows and 2% for energy use (Pellerin et al., 2013). Thus, crop fertilization is a major source of GHG emissions (Naudin et al., 2014). Manufacturing and transporting fertilizers account for additional GHG emissions, between 2% and 3% in France.[2] However, some crop species such as legumes[3] do not need nitrogen fertilizers.

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[1] See Karstensen et al. (2013) for a detailed analysis of the carbon emissions associated with deforestation and soybean exported from Brazil in the last decade.

[2] Calculated from data in Naudin et al. (2014).

[3] Grain-legumes belong to the Fabaceae family and cover a wide variety of species (such as pea, faba bean, lupin, soybean, lentils, and beans). Their common characteristics are to fix atmospheric nitrogen through symbiosis with soil bacteria to produce protein-rich grains (average of 22 to 38% protein in dry matter) harvested for feed or food. The European terminology distinguishes protein-rich legumes (comprising protein-rich peas, lupins and faba beans), historically oriented towards use in animal feed in the aftermath of the Second World War, from traditional dry legumes used mainly for food (lentils, peas, beans, chickpeas). Throughout the world, grain-legumes used for food are commonly called pulses, which does not include soybeans. Soybeans, classified both as a protein-rich legume and an oilseed, constitute a specific category because of their dual richness in oil and protein. Voisin et al. (2014) provides statistical data on changes in the place of legumes in cropping systems.

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Legumes have several advantages; primarily, they fix atmospheric nitrogen in the soil naturally and thus do not need nitrogen fertilizers. Therefore, they contribute to reducing N2O emissions compared with conventional crops (wheat, maize, barley, rapeseed) (Dequiedt and Moran, 2015; Carrouee et al., 2002). For instance, Jeuffroy et al. (2013) demonstrated that legume crops emit around five to seven times less GHG per unit area compared with other crops in France. Moreover, the grains from legumes are richer in protein than cereal crops and present interesting nutritional values for feeding livestock (Gueguen and Duc, 2008). Legume feed would thus reduce Europe's great dependence on soybeans imported from America (contributing to deforestation). The nutritional and other technico-functional properties of grain-legumes are also advantages for processed food products (Curran, 2012) and, more broadly, in the pharmaceutical sector and in chemistry (Voisin et al., 2014). Yet, despite these benefits and interesting use properties, grain-legumes are hardly cultivated in France or Europe and are not cultivated on a large scale throughout the world. As regards global land use, Jahn et al. (2015) report that pulse crops occupied less than 1 million square kilometers in 2012, whereas cereals, 7 million, and oil crops near 3 million. These authors also noted that there would be dramatic environmental benefits if farmland were more diversified.

In France, grain-legume harvested crop area has been declining for several decades, accounting for less than 3% of French field crop acreage, much less than in North America and Asia. For instance, in the USA, soybean acreage accounts for nearly 33% of the harvested crop area, whereas pulses are around 1%. French pulse crop acreage is around 0.2% whereas dry peas, faba beans and lupins (the three main grain-legume crops in France) account for 1.8% and soybeans for 0.6%.[4] However, Europe has granted considerable subsidies to increase legume cultivation, particularly for those rich in protein. Faced with continuing decline and the failure of its previous policies, the European Union has begun to question the reasons for this failure (Schreuder and de Visser, 2014).

Although many studies in agronomy have shown the important agro-ecological effects of inserting grain-legumes in cropping systems due to their various ecosystem services (Carrouee et al., 2002; Munier-Jolain, 2002; Nemecek et al., 2008), little attention has been paid to the economic factors that may explain why, in practice, these crops are marginalized in agriculture. In this paper, we argue that this situation has resulted from technological lock-in, and that the complexity of these changes can be best understood by drawing on the theoretical frameworks of social coevolution and socio-ecological coevolution (Kallis and Norgaard, 2010). To understand the reasons leading to this lock-in of the agrifood sector, which marginalizes grain-legume crops in France (and more broadly in Europe), this study analyses the coevolution of the main actors in the agriculture and agrifood sectors (researchers, farmers, cooperatives, feed and food manufacturers, and consumers). Our historical approach highlights the ways in which certain initial choices and self-reinforcing mechanisms have resulted in this lock-in (Arthur, 1989). Understanding the factors that hinder grain-legume development is essential to finding successful ways to promote grain-legumes, so as to contribute to more sustainable agriculture. Following the methodological pluralism proposed by Norgaard (1989), this study combines knowledge from economics, agronomy, ecology, sociology, genetics, food process engineering, and nutritional science. Several researchers from different disciplines have worked on this research in order to move beyond traditional disciplinary approaches (Brandt et al., 2013).

While this paper focuses on the marginalization of grain-legume crops and their use, this problem deals more broadly with the lack of crop diversification in agriculture, and thus the trend to shortened crop rotations (Bennett et al., 2012). Field crop specialization is a major feature of most European countries, and has been inherited from the agricultural revolution of the post-war period (Vanloqueren and Baret, 2008, 2009). Particularly in France, from the 1950s to the 1980s, the intensification of agriculture through increased mechanization, use of synthetic inputs, and adapted genetic selection led to crop specialization, which has continued ever since (Meynard et al., 2013). Today, any attempts to diversify cropping systems in order to reduce chemical use are faced with a highly organized supply chain and R&D in the agriculture and in the agrifood sectors (Gliessman, 2015). Feed and food markets have also developed conjointly with major crops, with the result that minor crops have been gradually relegated to the background along with the ecosystem services they provide. One major of these services of grain-legumes is supplying nitrogen, in addition to providing food and feed for agriculture.

Our purpose is to show how the joint evolution of the agriculture and agrifood sectors has particularly affected grain-legume crops, and to analyze the lock-in situation that hinders the development of grain-legumes. The following section discusses the theory of path dependency and draws on the major self-reinforcing mechanisms discussed in the literature to explain the technological lock-in of a certain pathway in the agrifood system. In Section 3, these factors are put into perspective through an historical analysis of the French agriculture industry and the coevolution of competition between cereals (major species) and grain-legumes (minor species). Section 4 discusses the current state of knowledge and solutions for encouraging diversified agriculture using grain-legumes. The final section concludes by highlighting the reversibility of the lock-in process if several actions are jointly undertaken to engage actors on a purposive transition path.

2. Path Dependency and Lock-in Throughout the Agrifood Sector

Coevolutionary frameworks explain how the relationships between values, knowledge, organizations, technologies, and environments can lead to lock-in by creating strong interdependencies between actors within a production system (Kallis and Norgaard, 2010). The incumbent production system, built over time, has stabilized through multiple technical and social relationships that ‘lock’ the actors in their choices.[5] Compared with traditional economics, lock-in analysis takes a different approach to explain ‘choice’ in production systems that integrates the complexity of the inter-dynamics of several mechanisms, such as scale economies (for a synthesis, see Dosi and Nelson, 2010). The evolutionary economics approach chosen in this article foregrounds historical choices and interactions across systems in order to understand the barriers to change.

The self-reinforcing mechanisms that create lock-in and thereby discourage stakeholders from adopting alternative production systems have been identified in research adopting a comprehensive and historical perspective. Studies of technological lock-in have focused primarily on manufacturing, transportation (David, 1985; Arthur, 1989, 1994; Liebowitz and Margolis, 1995), and energy (Cowan, 1990). Some studies have also been conducted on the agricultural sector (Wolff and Recke, 2000; Wilson and Tisdell, 2001; Chhetri et al., 2010). In particular, the work of Cowan and Gunby (1996) and Vanloqueren and Baret (2008, 2009) show how academic agricultural research has focused primarily on one type of research paradigm, oriented towards agrochemicals and genetic engineering, to the detriment of a paradigm based on agro-ecology oriented towards crop diversity. Yet, crop diversity would provide a broader range of ecological services through their functional properties and would therefore enable a significant reduction in synthetic inputs (Stoate et al., 2009).

[4] Meanwhile cereal crops occupy more than the two-thirds of the harvested crop area both in France and in the USA (USDA data for USA, Agreste data for France).

[5] As explained by Geels (2011, page 25), the dominant system is “stabilized through various lock-in mechanisms, such as scale economies, sunk investments in machines, in infrastructures and competencies. Also institutional commitments, shared beliefs and discourses, power relations, and political lobbying by incumbents stabilize existing systems…consumer lifestyles and preferences may have become adjusted to existing technical systems. These lock-in mechanisms create path dependence and make it difficult to dislodge existing systems.”

In France, crop specialization based on the agro-chemical paradigm has been reinforced over time and grain-legumes have become marginalized (Fig. A in appendice) (Mignolet et al., 2014; Fuzeau et al., 2012). According to the latest French agricultural statistics, of the 14.2 million hectares of field crops in 2015, cereals cover 9.6 million ha (5.5 million of wheat) compared with less than 250,000 ha for grain-legumes. The surface of wheat is still increasing. Among the 60,000 French farms specialized in field crops, only one-third grow grain-legumes as well. For those farms, grain-legumes cover 8% of the field crop area. Cereals such as wheat, barley, and maize now cover 60% of France's field crop area. France exports 45% of its cereal production. This crop specialization relies on a high use of chemicals leading to increasing environmental problems. This specialization can be explained by evolutionary economics, which highlights several self-reinforcing mechanisms that created increasing returns to adoption in the agriculture and food industries for major crops.

2.1. Specialization in Arable Crops and the Dominant Agro-chemical Paradigm

The dominant farming system appears locked-in around a technological paradigm based on intensive use of chemicals (fertilizers, herbicides, pesticides, etc.) associated with a low diversity of cultivated plant species. This situation is the result of an historical process linked to the development of pesticides and mineral fertilizers that have increasingly become the technical focus in cropping systems.

As Meynard and Girardin (1991) and Lamine (2011) have shown, the increasing availability of pesticides promoted a change in crop management. For example, in northwest Europe in the 1980s, the sowing of wheat was moved several weeks earlier in the fall to increase crop productivity. Yet this early sowing, which increased the risk of pests and disease, was only possible with additional herbicides, insecticides, fungicides and growth regulators. Similarly, the crop rotations were simplified: in conjunction with the decline in mixed-farming systems, crops such as alfalfa and other forage crops disappeared from many farms in the 1970s. Starting in the 1990s, grain-legumes in turn disappeared from the most common rotations. This legume regression in cropping systems was accompanied by an increase in nitrogen fertilizer doses and associated GHG emissions. Yet legume reduction is not the only factor that lead to increased use of mineral nitrogen fertilizer in cereal crops; reduced use of organic animal waste as fertilizer (linked to the decline of mixed farming systems) and increased demand for higher cereal yields contributed as well (Voisin et al., 2014). These simplified cereal rotations led to an increase in pest and disease pressure on other crops and therefore to an increased use of pesticides (Wilson and Tisdell, 2001). In addition, simplified crop rotations based on the frequent return of cereals (Fig. 1) promoted root diseases that reduced the plants' ability to use fertilizers and, therefore, led to higher fertilizer doses (Schoeny et al., 2003). Thus, Mignolet et al. (2012, 2004) observed that the total nitrogen dose applied has been increasing since the 1970s (Fig. 2), both as a result of these factors and higher yields for wheat, which is the most cultivated plant in France.

The authors of this study on the Paris basin, an area emblematic of field crops in France,[6] combined multiple data sources and found that the increased use of chemicals (pesticides, herbicides and mineral fertilizers) has caused an increasing contamination of underground and surface water over the last 40 years. Pollution has increased in almost all rivers and water bodies, sometimes reaching critical levels in the regions specialized in field crops. Concentration measurements taken by the French *Observatoire National de la Qualité des Eaux Souterraines* [National Centre for Groundwater Quality, ONQES], have indeed shown a steady increase in nitrate concentrations for nearly 30 years, leading to an increasing amount of the water in field crop regions being declared undrinkable (Mignolet et al., 2012).

A major consequence of this increasing specialization of field crops is increasing negative environmental externalities associated with agricultural pollution and loss of biodiversity. In addition, it seems that such a system may have less economic efficiency given the rising costs of synthetic inputs relative to the wheat grain price. Loyce et al. (2012) have shown that with lower wheat grain prices in 1990s and early 2000s throughout the world, low-input crop management for lower N input systems were more profitable. But in the context of very high wheat prices (as at the end of the 2000s) "high-input systems making use of high-yielding cultivars are currently more profitable" (p. 174). The authors concluded that the tradeoff between profitability and environmental benefits is very sensitive to grain and oil prices. There is less dependence on oil prices, however, because, according to the authors' calculations, the elasticity between the price of nitrogen fertilizer and oil is 0.55 (i.e. an increase of 55% in N fertilizer costs for a 100% increase in fuel costs, page 170). Thus, although production with intensive synthetic inputs has clear energy and environmental disadvantages, the profitability of this high-input system depends mainly on a high wheat grain price. How has our agricultural system ended up in this situation? This paper draws on the main self-reinforcing factors identified in the literature to the agriculture sector in order to explain its trajectory towards lock-in.

2.2. Increasing Returns to Adoption and Self-reinforcing Mechanisms of Major Crops

The concept of increasing returns to adoption (IRA) coined by Arthur (1989) explains why the initial choice of a production system can be reinforced over time, creating a process of path dependency. IRA is a key concept in the theory of technological lock-in developed in evolutionary economics. This concept seeks to explain how one technology manages to dominate other alternative technologies. The more a technology is adopted in a sector, the more its performance improves and the more other compatible technologies develop conjointly around common standards. This creates a socio-techno-structure that becomes increasingly difficult to change in order to enable alternative technologies to develop, even though they may be recognized as more effective.

This lock-in is reinforced by a combination of several mechanisms. By the combined effect of economies of scale (unit cost reduction by production volume), of learning by doing (performance improvement through experience) and network externalities (the larger the number of users, the greater the value for each of them), the result is that the more a production system is adopted, the more its production costs decrease, and the more its usefulness increases at the expense of alternatives. These returns to adoption are thus termed 'increasing'. In that way, as Arthur (1994) explains, a technology is not necessarily chosen because it is the best, but it is the best because it is chosen. Uncertainty about alternative solutions that have received less investment and learning, and the inherent cost of change, reinforce the initial choice even further over time and can even lead to a situation of irreversibility (Liebowitz and Margolis, 1995).

For agriculture, the more major cereal crops have increased in rotations, the more their technical and economic performance has improved. This has in turn promoted their adoption at the expense of other species whose yields are lower and/or more variable, in particular through less advanced technical practices and plant breeding. Among these self-reinforcing mechanisms in favor of a few dominant species, the search for economies of scale upstream and downstream in the agro-industrial system is a major factor. Upstream, as R&D generally focuses on specific plant species in terms of varieties (breeding and seed distribution) and chemical pesticides (licensing, distribution), investments have been based on the prospects for large production volumes to earn more return on those investments. At the farm level, specialization may be explained by the greater ease of acquiring technical skills,

[6] These figures are also available at the national scale in a French article by Mignolet et al. (2014).

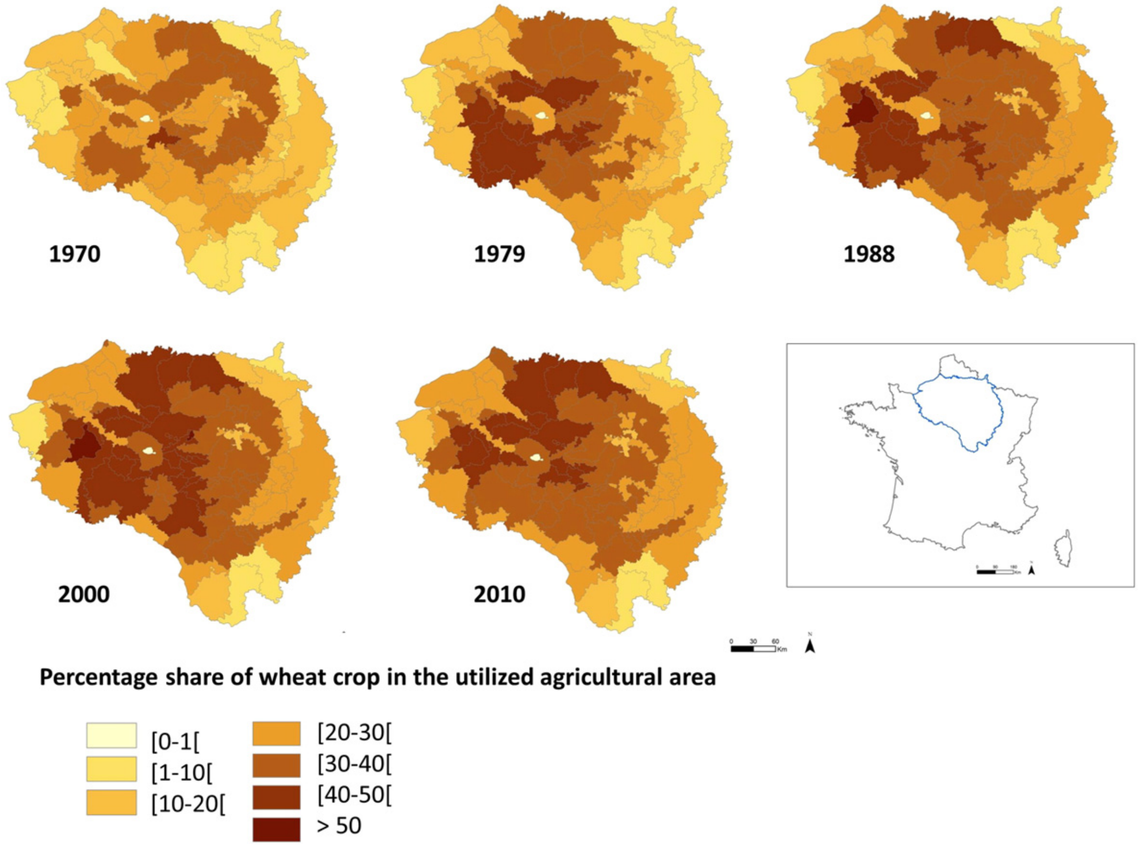

Fig. 1. Proportion of wheat crop in the agricultural land area of the Paris basin 1970–2010 (from Mignolet et al., 2004, 2012).

amortizing the cost of farm equipment, and organizing the work based on the few crops in which it specializes. Downstream, the storage, processing, and marketing tools follow the same logic: the specialization in a few dominant species leads to economies of scale, reducing the marginal cost of using a given plant species. This search for economies of scale has contributed to a simplification of cropping systems that results in shorter rotations, as observed in France (Schott et al., 2010; Fuzeau et al., 2012).

This simplification of systems has also been reinforced over time by their strong dependence on the organization of the agrifood industry and on the markets and politics interacting with agriculture (Magrini et al., 2015). The industrialization of agrifood supply chains has been accompanied by a growing number of agricultural standards and production norms, which contributes to technological lock-in (Busch, 2011). For example, the technological requirements for high protein levels in wheat facilitate processing and cooking (both for soft wheat in bread and for durum wheat in pastries). This requires, in return, high nitrogen doses in crops. In addition, the logistics of storage and collecting organizations, which are focused on major species to supply the food industry, are not adapted for innovative systems reducing inputs, such as intercropping cereals and legumes, even though this innovative crop system has many agro-ecological benefits (Corre-Hellou et al., 2011; Naudin et al., 2010). A study of farmers' cooperatives collecting wheat in the south of France showed that in the previous decades, the logistics infrastructure was based on large silos divided into small-sized cell units (Magrini et al., 2013). Yet a greater diversification of harvested crops (species or production mode) would require a larger number of storage cells in order to preserve the qualities of crops during the various operations such as sorting and blending and to extend storage for better business opportunities. Since the initial investments in large silos have not yet amortized, however, cooperatives are reluctant to change their logistics organization to include greater crop diversity.

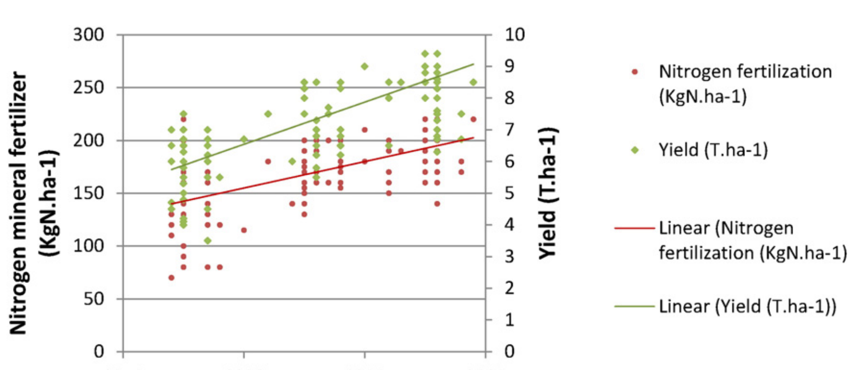

Fig. 2. Time-course change in wheat yield (in metric Tons per hectare) and the total rate of mineral nitrogen fertilizers (in Kilograms of N per hectare) applied to wheat crops in France, 1970–2000 (from Mignolet et al., 2004, 2012).

Therefore, minor crops are neglected in storage strategies and often quickly sold to make room for major crops that will completely fill the silo and thus contribute to its amortization.

We now turn to an historical examination of these lock-in mechanisms in favor of cereals to explain why grain-legumes occupy a marginal place despite their agro-environmental benefits and the public funding they have received.

3. Marginalization of Grain-legumes in the Agrifood System: An Historical Perspective

The specialization of French field crops in favor of cereals at the expense of grain-legumes can be explained by these self-reinforcing mechanisms triggered by historical choices.

3.1. Path Dependency: The Historical Preference for Cereals

As Thomas et al. (2013) found in their historical analysis, in the 1960s, in order to meet the goal of self-sufficiency in cereals, the European Economic Community implemented price support for cereals, committing themselves in return in trade agreements with the United States to allow entry of unlimited amounts of oilseeds without customs duties. These international agreements promoted massive imports of soybean meal,[7] rich in protein and inexpensive for livestock farms, at the expense of legumes that could be grown in France and more broadly in Europe. Moreover, this contributed to the increasing return to adoption for soybeans on the American continent.[8] But in 1973, the US administration banned the export of soybean (due to severe weather conditions that strongly reduced the American soybean harvest) resulted in the European authorities realizing that their livestock systems were strongly dependent on imported soybeans for feed. Different "protein plans" were then put in place to re-start European production of protein-rich legumes adapted to the European climate (Meynard et al., 2013; Magrini et al., 2015). New varieties of grain-legumes, such as protein-rich peas, were created by public research. Protein-rich legume production (mainly pea) then increased steadily until the late 1980s (Fig. 3).

Yet in the early 1990s, a shift in the Common Agricultural Policy (CAP) occurred: price support was scaled down and replaced with direct aid payments to farmers. Since this reform, the grain-legumes surface area has decreased because the reduction in direct subsidies and the variations in price support from one year to the next were not enough to compensate for the competitiveness gap between grain-legumes and other species, such as imported soybeans for feed manufacturers and cereals for farmers. Public policies, therefore, failed to correct the balance of power that was gradually created between major and minor species through lock-in. Although the growth in cereals has enabled the EU to achieve food self-sufficiency since the early 1980s, the progression of wheat in cropping systems continued, reinforced by the use of pesticides as explained above. Until the CAP reform of 1992, these cereals continued to receive subsidies despite a production surplus, a policy which has been termed 'subsidized exports'.[9] In view of the factors specified in Section 2, this period was one of IRA consolidation for cereals.

In addition, as Oliviera and Schneider (2014) have shown, the global soybean complex has strengthened its power through flexing (defined by its multiple use for feed, food, fuel and other industrial uses) and through agribusiness actors that positioned themselves to better control both the upstream and the downstream of supply chains throughout the world and "to gain even greater control over further and anticipated flexing" (p. 14). Globally, the USA remains the first producer of soybeans (with 90 million metric tons in 2013) although Brazil is close behind.[10] Worldwide, in 2013–2014, about 280 million metric tons of soybeans were produced, 16.4 million metric tons of which were for food (6%), 250 for crush use (90%), and 14 million for whole grains in feed (4%).

International agreements in recent decades have also largely contributed to maintaining soybean imports in Europe, thereby leaving little opportunity to develop other grain-legumes as alternatives for feed. For instance, the Blair House agreement of 1992 between the European Union and the USA limited the aid that Europe would grant for developing oil- and protein-rich plants in Europe. In the 2000s, no new subsidy plan would be implemented (Hache, 2015). It was not until 2010 that new policies supporting plant proteins appeared, but the variability of these subsidies and their weak current level has not resulted in a significant increase in surface area (Schneider and Huyghe, 2015). Thus, the sociotechnical dominance of soybeans combined with international agreements reinforced the marginalization of grain-legumes in France and in Europe. This situation illustrates the ways in which public policy interventions can have long-term consequences that go beyond the short-term horizon initially targeted: "consequences might be desirable in the short run, but disastrous in the long run. This is particularly important for the agrarian sectors in which subsidies play an important role in the development of the system" (Wolff and Recke, 2000, p. 168).

For agriculture, the fall in grain-legume surface areas from the early 1990s can be explained by the widening gap in farmers' annual margins compared to cereal crops. The annual gross margin for grain-legumes is on the order of 2 to 6 times less than that for non-legume crops in France (Dequiedt and Moran, 2015; Schneider and Huyghe, 2015; LMC International, 2009). The less competitive position of protein crops may be understood through this evolutionary perspective. Seen through the lens of increasing returns to adoption, after the initial choice was made in trade agreements between Europe and the United States, cereals progressed greatly, thereby reinforcing crop specialization both upstream and downstream in the agro-industry (Fig. 4).

Among these factors, some are essential: the economies of scale and learning that promoted the growing gap in yields between species, and the interdependence between upstream/downstream industries that strengthened investment in cereals.

3.2. Learning Effects and Investment Choices: the Gap in Grain-legume Yields Compared to Cereals

Beyond economies of scale seeking to reduce the unit cost at various stages of production, transport, and transformation involved in the growth of major crops (see Section 2), learning effects seem particularly pronounced in the area of mineral nitrogen fertilization of cereals. Since the Middle Ages, legumes have been grown in rotation with cereals in mixed farms associating crops and livestock. The source of nitrogen for cereal crops came both from the nitrogen available in the soil following the legume crop and from organic animal waste. Yet in current farming systems where livestock and crops are separate, in order to meet crops' nitrogen needs, which is necessary for achieving high yields, the use of mineral fertilizers was imposed because it was considered more reliable than legumes in crop rotations. The advancement of knowledge in this field and developments in the production of mineral fertilizers

[7] Friedmann (1993) offers a deeper historical analysis of the postwar international agreements that have shaped our agro-food system, "The US supported the European protection of wheat and dairy products, even at the very high level needed to keep out efficiently produced and subsidized US exports. In return, the European Community exempted maize and soybeans from the import controls of the Common Agricultural Policy…The 40% of Marshall aid that went to food and agriculture in Europe was concentrated upon imports of feedstuffs and fertilizers for agricultural reconstruction" (pages 35–36).

[8] Soybean production has grown strongly in the USA: from 18 million metric tons in 1961 to 90 million in 2013 (FAO).

[9] For instance, data in Desbois and Legris (2007) show that in 1992, the crop price (with direct subsidies) was around 20€/quintal for wheat in France, whereas the world price (based on the Chicago market) was 10.3. After the CAP reform, those prices were respectively 11.5 and 13.9 (in 1998). The net wheat margin for the farmer was still positive in 1998 thanks to the subsidies received, but those subsidies were less determined by market price than they had been before the reform.

[10] Data from the IGC (International Grains Council) http://www.igc.int/.

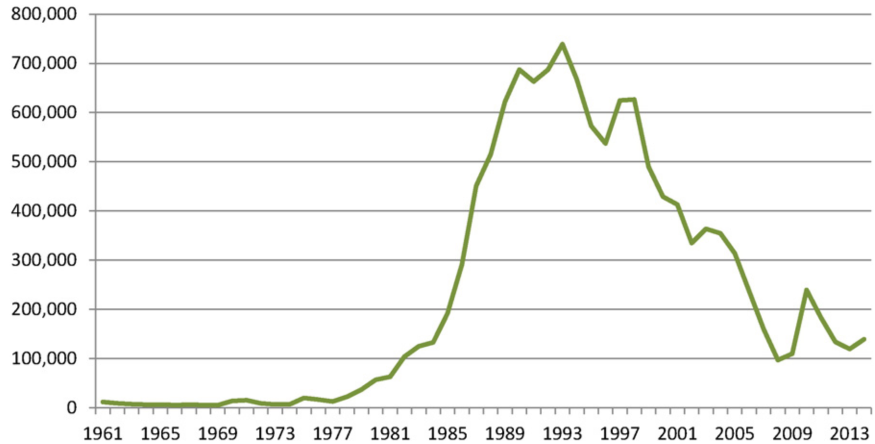

Fig. 3. Time-course change in arable area of protein-rich peas (hectares), which is the top grain-legume grown in France.
Source: Agreste — French Statistics on agriculture.

enabled an increase in grain yields. From the 30 million kilograms of mineral fertilizers used in the early 1960s, the volume has stabilized at around 70 million, with a current average of 164 kg/ha for wheat crops.[11]

Today, faced with the rising cost of energy and the need to reduce agricultural pollution due to chemical fertilizers, there have been incremental innovations in conventional technology aimed at optimizing fertilizer use. For example, the desire for more precise adjustments of rates and dates for nitrogen application in crops has led to more precise doses of fertilizer throughout the crop cycle and to specific fertilization programs guided by satellite images (such as the Farmstar program, Labarthe and Rivellie, 2013). The lock-in of the production system, however, tends to rule out more radical innovations that would re-design cropping systems to include more grain-legumes, which would enable a greater reduction in nitrogen fertilizer use throughout the entire crop sequence, including intercrops (Pelzer et al., 2012). Recent studies have shown that at the scale of the entire crop sequence, the gross margin of a crop system including peas is not lower than a system without peas (Jeuffroy et al., 2013). However, the economic performance of grain-legume crops in farms is evaluated primarily through yield indicators and annual gross margins and rarely by inter-annual gross margins. Inter-annual accounting generally reveals a rotational benefit for the farmer, as grain-legumes both reduce fertilizer needs and increase the quality and yield of the following cereal (LMC International, 2009).[12] This evaluation problem results from a lack of cost-accounting on a multi-year scale that would take into account this kind of pecuniary externality between crops. Few farms have technical advice able to explain how to evaluate the cropping system to determine the multi-annual net profit (Meynard et al., 2013).

The increase in nitrogen fertilization of cereal crops has been even greater since the dramatic increase in wheat yields (fostered by fertilization) has focused actors' attention on developing food products based on cereals, primarily wheat (Hesser, 2006). With a growing volume of agricultural production and quality, businesses have perceived considerable opportunities for food markets through this commodity. Consumption of wheat (in its various forms, bread, cake, pasta, etc.) has in fact doubled in France between 1970 and 1980 and continues to grow: from 87 kg/year/person in the middle of the 1990s, it has grown to 105 kg/year/person in the late 2000s. Conversely, grain-legume consumption has fallen sharply: from 7.3 kg/year/person in 1920 to less than 1.4 since the 1980s.[13] Grain-legume surface area for domestic human consumption has also shrunk from nearly 200,000 ha in 1960 to less than 30,000 ha in the early twenty-first century.

These food preferences are reflected in terms of the differential change in yields. Yields for legumes directly used for human consumption (lentils, dry beans, etc) have barely progressed. Concerning protein-rich plants (including protein-rich peas, lupins and faba beans) mainly used for animal feed, the wheat/pea differential is also revealing of demand-side preferences. Between 1960 and 1980, the yields of wheat and protein-rich pea have both more than doubled. However, from the late 1980s, the pea yield differential with wheat expanded (Fig. 5). This happened in spite of public research efforts on peas, which was used as a model by INRA (the French National Institute for Agricultural Research) for genetic research on protein-rich legumes. One reason for this is that the yield increase in wheat varieties with semi-dwarf genes enabled nitrogen doses to be increased without increasing the lodging problem.[14] Even though genetic progress has also been made for protein-rich legumes as regards lodging, their yields capped at a significantly lower level than that of cereals, and the curve of the national average yield in the last 10 years even shows a clear downward trend. The pea yield was near 80% of that of wheat in 1990, falling to 50% in the late 2000s. It should be noted that efforts at varietal selection for peas are more recent, and business investment in selection is much lower than that for major species (see *infra)*.

Several other reasons may explain this gap. Because the pea was planted too frequently in the same field during the 1980s (a period of higher European subsidies), some croplands were infested with *Aphanomyces euteiches,* a root disease for which, even today, there are no effective means for control. The farmer must wait several years for that pathogen to disappear from a field. When peas have not disappeared entirely from crop rotations, they have often been relegated to poorer land. Yet, moving crops to less fertile land itself seems to be a self-reinforcing choice, as farmers prefer to reserve the best land for species with higher yield potential.

In addition, due to the key role of pesticides within the logic of the dominant cropping systems (Wilson and Tisdell, 2001; Meynard and Girardin, 1991), companies that market these inputs have become the main source of advice to farmers (Lamine, 2011; Jacquet et al., 2011). To fight against pests, their advice usually focuses on chemical solutions, which are simple and offer spectacular efficacy, rather than preventive agronomic practices, such as the lengthening the crop rotation that would allow more space for legumes. It is true, however, that advising

[11] From French Statistical Data on agricultural practices (SSP) 2006.

[12] This report presents several calculations and results for grain-legume cultivation in several European regions.

[13] In recent years an average of 0.6 kg/person/year of lentils, 0.6 kg/person/year of dried beans, and between 0.1 and 0.2 kg/person/year of each of the other pulses such as split peas, chickpeas, and faba beans (from Agreste-French Statistical Institute).

[14] Because of increasing mineral fertilizer inputs, the number and weight of wheat ears increased, causing more lodging problems. By introducing semi-dwarf genes in 1970 years, the stem height decreased to reduce lodging, allowing continued growth in fertilizers to augment grain yields.

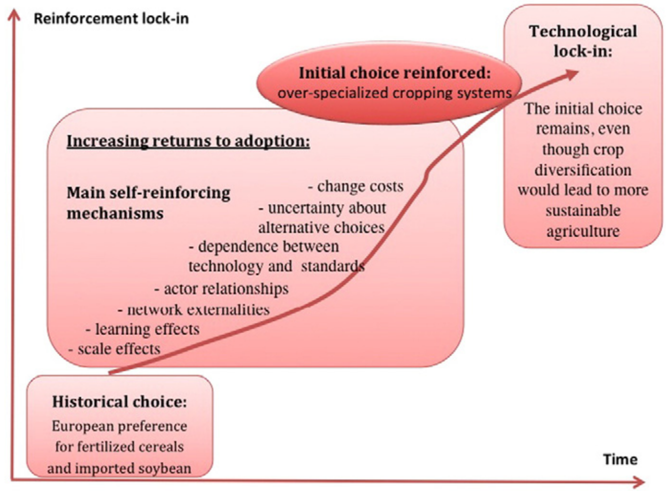

Fig. 4. Lock-in of the agrifood production system and the marginalization of grain-legume species.

about long crop rotations is more complex and may have a less direct effect than using chemicals.

Thus, the subsystem of knowledge and research underlying agriculture is based on a logical system that prevents even considering the benefits of crop diversification, including the ecosystem services of legumes. A bibliometric analysis of the French agricultural press at the end of the 2000s shows the very low frequency of articles offering farmers reference data and advice on crop diversification, including legumes (Meynard et al., 2013). Moreover, agricultural institutes providing advice remain focused on major crops (wheat, maize, rapeseed, and sunflower). In France, a compulsory tax on major crops partially funds those institutes, whereas some grain-legumes species do not yet have such a tax. The greater the production of major crops upstream, the more funding these institutes have for R&D on major crops. Moreover, these agricultural institutes are specialized by crop; in other words, cereals, oilseeds, and protein crops are studied in separated institutions, which does not favor crop diversification studies.

3.3. Industry Interdependence Upstream and Downstream in the Supply Chain: Preferring Cereals for Food and Imported Soybeans for Feed

The competitiveness differential between cereal and grain-legume species has grown even larger because an additional historical preference was given to European grain-legumes: they were considered almost exclusively as animal feed, placing them in direct competition with soybean meal, which provides cheap protein in large quantities

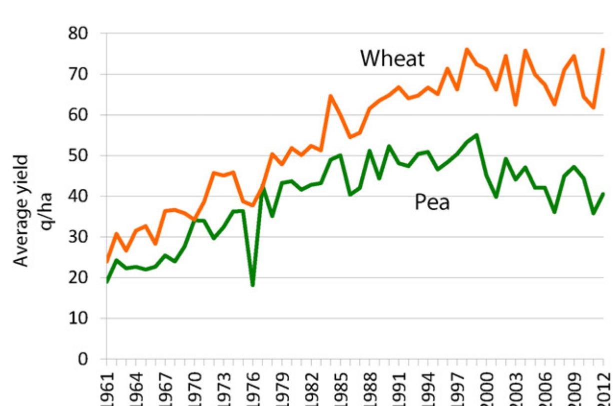

Fig. 5. Time-course change in yields of protein-rich pea and wheat in France, quintal per hectare (q/ha).
Source: FAO Stat.

(Gueguen and Duc, 2008). This orientation driven by public institutions has meant that research and private stakeholders have neglected progress towards better promotion in high-value outlets such as human food for grain-legumes. Yet today, faced with competition from other raw materials including other co-products (rapeseed meal, or dried distillers grains primarily for ethanol), the use of grain-legumes in animal feed has fallen sharply. From 3 million metric tons of protein-rich peas produced for feed in France in the late 1980s, fewer than 500,000 metric tons are today destined for livestock. Facing stiff competition in the market for concentrated feed, and with feed systems being built on the promotion of cereals, protein-rich grain-legumes represent less than 2% of feed formulas in France (and in Europe[15]); they are considered as a simple adjustment variable (Meynard et al., 2013). Their inclusion in formulations has particularly fallen in recent years (see Fig. 6).

As explained above, whether for producers or for users, the increasing returns to adoption for major species have created a competitiveness gap with grain-legumes, that price and production support can no longer compensate for in France. As suggested by Thomas et al. (2013), this public support, which has also been unstable over time, has not resulted in lasting incentives for their cultivation, unlike the market dynamics that have created significant outlets for cereals and more recently for oilseeds used for biofuels and food oil. The development of bio-fuels and of rapeseed and sunflower oils has contributed to the growth of these crops since the late 1990s, with their meals providing new sources of protein-rich feed, and in a sense being positioned as “flex crops” like soybeans. In addition, the reduced area of grain-legumes sends a signal of decreasing supply, prompting formulators to exclude their use in feed for fear of a lack of supply. They then become an occasional substitute depending on the ratio of market price competition between raw materials, which for farmers means that it is risky to grow them compared to other species.

As with human consumption, the low investment in research and development on these species has not created market opportunities with greater added value that would encourage their wider cultivation in France. Consumption of pulses declined in France during the twentieth century and half of current consumption comes from imports, while both consumption of cereals and animal products have increased significantly in recent decades (Combris et al., 2011). The drop in eating pulses has occurred together with the growth in mass consumption of meat, which itself has followed an increase in household incomes as observed throughout the world (Tilman and Clark, 2015). Strong socio-cultural factors affect pulse consumption. According to a survey of consumption on a representative group in France, pulses suffer from an image as being ‘old-fashioned’ and have been traditionally called ‘the poor person's meat’.[16] In addition, this study also found that changing lifestyles in favor of fast-cooking foods have made legumes less attractive (Champ et al., 2015).

Some niche markets have, however, been created for functional ingredients, such as starch and pea proteins or the market for lentils or beans with a quality label (such as Protected Designation of Origin),[17] as well as export markets such as faba beans for Egypt or green peas for India (Magrini et al., 2015). These niches provide producers with higher prices than for feed outlets, providing more incentives to farmers. Yet to date, these species are generally poorly represented in French high-processed foods. Studies from the *Groupe d'Etude sur les Protéines Végétales* [Study Group on Plant Proteins] show that today, the majority of plant proteins used in the food processing industry comes from wheat in France and soybeans in the rest of

[15] Data from the EFIP European Feed Ingredients Platform, http://www.efip-ingredients.org.

[16] The image of pulses as food for people of modest incomes became stronger during the First and Second World Wars, when the French government published nutritional guidelines advocating pulses as they were easy to preserve and provided nutritional qualities of satiety and calories.

[17] See Voisin et al. (2014) for maps of pulses production in France and their various quality labels.

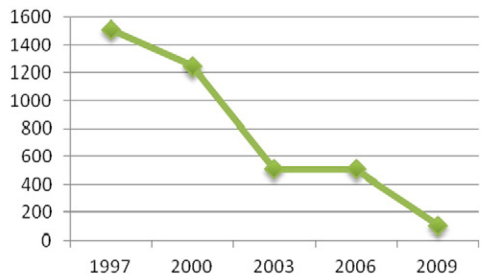

Fig. 6. The drop in protein-rich peas use in manufacturing animal feed in France (in thousands of metric tons).
Source: Agreste-French statistics.

the world.[18] These results highlight the coevolution of the supply and demand side of the agrifood sector.

Finally, as mentioned above, the organization of public and private research in France has itself helped specialize and promote research for species for which the food industry wants to develop outlets, such as cereals and particularly wheat. Research activities dedicated to plant breeding are a case in point. Bonneuil and Thomas (2009) showed that INRA has gradually withdrawn from creating varieties (more than 100 species in 1975 to less than 10 in 2005), with a low point in 2003 when the decision was made to focus on few species in overall plant breeding activities. Of these, only one grain-legume target was chosen: the winter pea. By greatly reducing genetic and breeding research on minor species, INRA thus ceased to counteract private companies' concentration of plant breeding on the dominant species linked to their market-based thinking (Meynard et al., 2013). Currently, in France there are 6 companies with a breeding program on peas, whereas there are more than 13 for wheat. The number of wheat varieties published in the European Union's Common Catalog of Plant Varieties is also much greater than for field peas or field beans (Fig. 7).

This agro-industrial system (both upstream and downstream of the supply chain including research institutes) has contributed to the increased specialization of field crops in France (and more broadly Europe) through a strong dependence of agriculture with chemicals. Meanwhile, environmental concerns are increasing, and eating habits are now being questioned with an awareness of the excess of animal calories in human diets which questions also the sustainability of Western diets. Can these two related considerations, environment and nutrition, help to build a new pathway towards a superior technology based on more diversified agriculture in favor of grain-legumes? Following Rauschmayer et al. (2015), which knowledge systems would support this transition? Moreover, how does current knowledge allow us to better qualify the paradigm of crop diversity as superior?

4. Agro-ecological and Food Innovations: How to Promote Grain-legumes?

Some authors in the literature on technological lock-in distinguish different types of lock-in mechanisms depending on the knowledge of the actors, in order to describe the degree of reversibility towards alternative technologies (Liebowitz and Margolis, 1995). Indeed, actors' state of knowledge is determinant in their capacity to change, and prior to that, to decide to change. Therefore, if large-scale processes are initiated to unravel the lock-in, such as institutional innovations or new business strategies, those choices will be driven by the current knowledge of the actors involved. Knowledge is a fundamental driver of innovation. The advancement of knowledge in recent decades on the ecosystem services provided by legumes has proven the agro-ecological superiority of diversified agriculture (Nemecek et al., 2015). However, is this enough to qualify this paradigm as superior for the food system? Moreover, how can farmers have access to information about the benefits of crop diversification with legumes? In addition, how can we better take into account other dimensions such as human nutrition to increase society's interest in grain-legumes?

4.1. Moving Towards More Environmentally Sustainable Agriculture

The recent emphasis on ecosystem services (Millennium Ecosystem Assessment, 2005) modifies the framework for analyzing and managing agro-ecosystems (Wallace, 2007; Zhang et al., 2007). Agriculture has long been regarded as a supplier of food products to the detriment of other externalities that have proven to be major and highly disruptive to the environment. The expectations of agro-ecosystems have evolved. And it is scientifically proven that grain-legumes have significant ecosystem benefits that support the ecological intensification of agricultural systems, as there are many problems with nitrogen management in farming leading to pollution as well as agriculture costs.

Yet while institutions recognize those problems, decision tools for agriculture and better advice for farmers are still needed. The agro-ecological services of grain-legumes are poorly valued today in practice (see Section 3), because their ecosystem services are inadequately taken into account by farmers. With new knowledge about the nitrogen cycle between crops, advice and information about practices would encourage greater legume cultivation, such as: i) multi-year accounting to better assess rotational benefits; ii) measuring nitrogen balances in the soil after a legume to adjust nitrogen inputs on the following crop; iii) checking and adjusting nitrogen fertilization on the following crop, because the mineralization of nitrogen residue in the soil varies over time. The only way today to estimate the amount of nitrogen in the soil is to regularly use nitrogen management tools (Lemaire et al., 2008), iv) designing the rotation, including catch crops.[19]

In addition, institutional innovations would also foster better dissemination of agricultural advice in favor of legumes, such as the current reorganization of the French agricultural institutes. As mentioned in Section 3.3, a large part of agricultural advice comes from separate, crop-specialized institutions, making it difficult for them to offer advice about diversified crop systems. Starting in 2015, these agricultural institutes have begun to merge[20] and discussions are underway about establishing a tax on all grain-legumes to pay for advice, as has long been done for the major crops.

Although it is necessary to better justify the agronomic, environmental, and economic benefits of legumes in diversified crop systems by using adequate tools and advice, greater legume in agricultural production requires also encouraging downstream industries to offer new outlets with higher added value to increase interest in these crops.

4.2. Moving Towards Healthier Food

Since the environmental values of food are increasingly promoted, investment in grain-legume crops will also be encouraged if commercial interest in their use increases. Scientific knowledge on the importance of legumes in human nutrition has also advanced in recent years, particularly about the consumption of pulses (e.g. Curran, 2012 for a review). Moreover, new recommendations in Western countries, promoted

[18] Every two years, the GEPV (*Groupement d'Etude et de Promotion des Protéines Végétales* [Committee for Studying and Promoting Vegetable Proteins]) mainly composed of French industry producers, counts the number of food products containing protein vegetable matter in France. Although the number of products has increased regularly and even more so in recent years, the majority of these proteins are derived from wheat in 62% of products in 2011, compared with 19% for soybeans, 10% for faba beans, peas 6% and less than 2% for lupines.

[19] Most winter crops are not able to absorb the nitrogen supplied in the autumn (except rapeseed)[–semicolon–] their absorption capacity during this period is too low, which is why short catch crops between the harvest and autumn sowing can capture a portion of the nitrogen and prevent nitrate leaching (Plaza-Bonilla et al., 2015).

[20] See the creation of the new technical institute for oilseed and protein plants in June 2015, Terres Inovia, http://www.terresinovia.fr/.

	Wheat (excluded durum wheat)	Pea	Bean
France	304	61	20
European Union	2,234	392	134

Fig. 7. Number of current registered varieties of wheat, pea and bean grain-legumes, in France and in Europe, in 2015. (http://ec.europa.eu/food/plant/plant_propagation_material/plant_variety_catalogues_databases/search/public/index.cfm) As stated on the website: "catalogs are based on the registration of plant varieties in EU countries after they have been technically examined there and notified to the Commission. They are published in the Official Journal. Variety registration is a precondition for the certification of seed."

through national food programs such as *Programme National Nutrition Santé PNNS* [National Nutrition and Health Program] in France, calls for a greater reduction in the consumption of animal calories for health benefits (Friel et al., 2009).[21] This program calls also for an increased consumption of fiber and other compounds such as polyphenols and micronutrients. Those recommendations should promote interest in a greater consumption of grain-legumes. In France, however, direct consumption of vegetable proteins by eating pulses suffers from an outdated image, as mentioned above. The drop in pulse consumption can also be explained by the lack of a practical response to reduced household food preparation times. For example, the cooking time for lentils, which is the fastest pulse to prepare, is still two to three times higher than that for wheat and rice. There are few studies on genetics to reduce the cooking time of pulses (Vasconcelos Garcia et al., 2012). The dominant species in the food supply have benefited from varietal research to reduce their cooking time and to offer new products such as Ebly brand wheat or pre-cooked rice. The nutritional classification of pulses also remains unclear in the minds of consumers. Classified as starches alongside cereals in the French food pyramid, very few consumers cite legumes as a protein source.[22]

However, in other countries (Canada, USA) food pyramids have recently changed to positioning pulses as a valuable source of dietary protein and as meat alternatives.[23] For example, the USDA displays at the top of its dietary recommendations: "With protein foods, variety is key. Protein foods include both animal (meat, poultry, seafood, and eggs) and plant (beans, peas, soybean products, nuts, and seeds) sources".[24] We observe that pulse consumption is higher in Canada and the USA (around 4.5 kg/hab/year[25]) than in France, but, to our knowledge, there is no study analyzing the link between state-supported nutritional campaigns and consumption level of pulses. In France, some innovative products have recently entered the large retail market such as pre-cooked preparations mixing pulses and wheat. However, they remain positioned commercially as an alternative to traditional starches (pasta, rice) and not as a protein substitute. For this reason, discussions are underway at ANSES (French Agency for Food, Environmental and Occupational Health & Safety) among committees of experts to redefine the national food policy program. Will their findings lead to a revision of the nutritional classification of pulses? These institutional changes may affect the food industry's new product strategy and thereby affect farming upstream in its agricultural production strategies, leading to more crop diversification with grain-legumes.

Thus, the renewed interest in the nutritional features and properties of these grain-legumes strengthens the argument that the technological lock-in of the agrifood system is reversible. However, a stronger commitment from public authorities in France is called for, to support this change towards more sustainable agrifood system. The role of government agencies and politics is fundamental in managing such a transition. Considering the literature on transition management, one possibility would be a "purposive transition" with "deliberate attempts by state and/or non-state actors to translate shared visions into articulated pressure for change" that could "mould responses to the need for change on the part of those within the [incumbent] regime" (Genus and Coles, 2008, p. 1439). The positions that public research and development institutions will adopt in the coming years will be determinant to whether grain-legumes are promoted. The year 2016, named the "International Year for Pulses" by the FAO, may incite multiple actors to come together and work towards a new future for grain-legumes to promote sustainability.

5. Conclusion

The purpose of this paper was to analyze the technological lock-in situation that has developed in France in favor of cereals and at the expense of grain-legumes. This historical review has shown the difficulty in reversing the initial choices made, even for institutions receiving public funding, when increasing returns to adoption mechanisms are at work. The present study confirms the major consensus among evolutionary economists working with technological trajectories: history matters. Initial agricultural choices tend to be self-reinforcing over time, through various socio-economic mechanisms that together have shaped increasing returns to adoption. The means of production initially selected served as the foundation for the conventional regime, which is based on intensive use of synthetic inputs and around which the socio-technical system has been organized. Thus, although grain-legumes (grown alone or intercropped) have agro-ecological benefits (especially for nitrogen management), they are hardly present in conventional arable cropping systems. Initially, having been neglected compared with the greater investment in other crops (both upstream and downstream of the supply chain, especially in their industrial uses), the difficulties that farmers may face in growing them (such as irregular yields and disease/pest problems) are now perceived as even greater compared with the dramatic improvements that have been made for other species. Thus, the conventional agricultural system has gradually established a dichotomy between 'major' species and 'minor' species. The latter suffer today from a problem of increased competitiveness, which public funding can no longer counterbalance by providing specific crop incentives.

Currently, legumes' profitability for farmers is too low because (i) they do not calculate margins and yields at the scale of the rotation, losing sight therefore of legumes' benefits; (ii) low interest from the agro-industrial supply chain does not grant legumes a higher added value; and so (iii) the weakness of their yield does not sufficiently compensate for the associated reduction in mineral fertilizers.

This study has focused on the French case, but more broadly concerns European agriculture. One of the challenges of the agro-ecological transition is to give grain-legumes a more significant role by

[21] Environmental effects from the negative impacts of intensive livestock farming may also be taken into account.

[22] According to an ONIDOL-WFM joint study on "The perception of plant proteins" conducted in 2011, Study No. 1100886.

[23] See the food pyramid recommended by the Harvard School of Medicine in the USA http://www.hsph.harvard.edu/nutritionsource/healthy-eating-plate/; and http://www.hc-sc.gc.ca/fn-an/alt_formats/hpfb-dgpsa/pdf/food-guide-aliment/view_eatwell_vue_bienmang-eng.pdf for the Canadian government's food guide, in which "cooked pulses" are listed as an alternative to meat products.

[24] http://www.choosemyplate.gov, the official site of the USDA, Center for Nutrition Policy and Promotion, the equivalent of the French PNNS.

[25] Personal communication with Pulses Canada Association.

using better assessments of their techno-economic and environmental benefits. Insertion of legume crops in the carbon market has been put forward as a way to create new economic incentives for cultivating them (Dequiedt and Moran, 2015). However, faced with the gradual withdrawal of public price support and the problems of stabilizing the carbon market for legumes, we argue that new ways to economically promote these species must be found and that creating new outlets for them would better foster transition.

These new outlets need to be accompanied by a set of technological as well as organizational and institutional innovations, which also require changes in food processing and consumption. In other words, if co-evolution has favored lock-in, co-evolution is also needed to open up the production system to greater crop diversity. Institutional, political, and economic commitments are needed to change the incumbent technological regime (Berkhout, 2002). As for decision-makers, in order to strengthen the competitive position of grain-legumes among harvested crops within a more sustainable agrifood system, this study suggests that both state and non-state actors should be mobilized to engage in this purposive transition, with four priority actions: increase genetic research; improve farmers' knowledge in managing rotations with legumes and especially using less mineral fertilizer; develop accounting tools to better assess this benefit in monetary terms; and support food innovations to develop new outlets for grain-legumes.

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Appendix A. Appendice

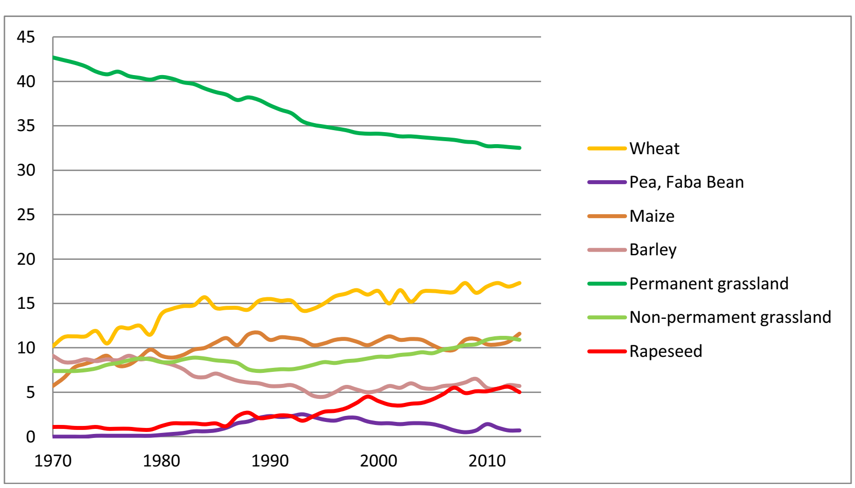

Fig. A. Time-course change in the protein-rich pea and faba bean areas (from 1970 to 2013), compared with the main harvested crops and the grasslands (as a % of the utilized agricultural area in France), adapted from Mignolet et al. (2014).
Source: SAA — French Annual Statistics on Agriculture.

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